ANALYZING THE SENSITIVITY OF VITICULTURAL PRACTICES TO WEATHER VARIABILITY IN A CLIMATE CHANGE PERSPECTIVE : AN APPLICATION TO WORKABLE-DAY MODELLING

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Abstract

Aims : The study aims at applying to a perennial crop the concept of "workable days" developed for annual crops by G. Kreher in 1955. A workable day is a day that provides conditions agronomically correct for work.

Methods and results : A survey among grapevine growers was carried out to collect their perception of practice sensitivity to weather variability. The study provided information on working periods, techniques and machinery involved, weather constraints and thresholds generally used by the vine growers, for 21 annual cropping practices. Pesticide spraying against powdery and downy mildew appeared to be the most sensitive to weather parameters. Therefore, this practice was selected for the purpose of modelling workable days, according to decision rules based on the postulate that all weather parameters should be within the acceptable ranges. The model was run over a period of 13 years (1998-2010). Analyses of the outputs pointed out a great variability in the number of workable days from one year to another as well as in the respective proportion of unfavourable weather factors involved in the reduction of workable days. A validation based on the analysis of the actual spraying practices realized over a period of 12 years (1999-2010) showed that 32 % of the treatments were done on a day characterized as not workable by the model. The errors could be attributed to periods of holidays and risky sanitary situations when decision rules had to be bypassed.

Conclusion : The model proved to represent rather well the decision rules use by vine growers to carry out their annual cropping practices in relation with the weather variability, within the area of study. The controversial role of the 'leaf wetness duration' weather parameter needs to be clarified; it may help to better parametrize the model. In order to improve its performance, the model should be coupled to a disease propagation model.

Significance and impact of the study : In a climate change perspective, modelling of workable days can be run with simulated climatic data. It may prove to be useful to adapt vineyard management strategies in terms of innovative cropping practices and equipment.

Key words : workable day, viticultural practice, weather factor, modelling, climate change

Résumé

Objectifs : L'objectif de l'étude est d'appliquer à une culture pérenne le concept de « jours agronomiquement disponibles », développé en 1955 par G. Kreher pour les cultures annuelles.

Méthodes et résultats : Une enquête a été conduite auprès de viticulteurs afin de connaître leur point de vue sur la sensibilité des pratiques viticoles aux aléas météorologiques. L'étude a permis de recueillir, pour 21 pratiques viticoles annuelles, des données sur les périodes de travail, les techniques et les matériels employés, les contraintes météorologiques ainsi que les critères de décision habituellement utilisés par les viticulteurs. La pratique des traitements phytosanitaires contre l'oïdium et le mildiou est apparue comme étant la plus sensible aux facteurs météorologiques. Cette pratique a donc été retenue dans le but de modéliser les jours agronomiquement disponibles, selon la règle de décision fondée sur le principe que tous les paramètres météorologiques doivent être compris dans les plages de tolérance. Le modèle a été testé sur une période de 13 années passées.

Conclusion : Le modèle fournit une représentation assez correcte des règles de décision qu'emploient les viticulteurs de la zone étudiée pour raisonner leurs pratiques culturales annuelles en fonction de la variabilité météorologique. Il est nécessaire de clarifier le rôle controversé du paramètre « durée d'humectation des feuilles » ; cela permettrait de préciser le modèle. Le potentiel du modèle de jours disponibles pourrait être amélioré en couplant ce dernier avec un modèle de prévision des maladies.

Importance et impact de l'étude : Dans la perspective du changement climatique, le modèle peut être utilisé avec des données climatiques simulées. Cette approche peut contribuer au développement de pratiques et de matériels de culture innovants et ainsi préparer l'adaptation des stratégies de conduite des vignobles.

Mots clés : jour agronomiquement disponible (JAD), pratique viticole, facteur météorologique, modélisation, changement climatique

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INTRODUCTION

A crop management plan is made up of a series of agricultural practices that a farmer needs to carry out according to a schedule, determined by the plant's cycle. Common practices include soil tillage, sowing, fertilization, disease control, and harvesting. For each of these practices, the farmer must try to aim for the most favourable timeslot so that he can expect the highest harvest potential. For instance in the case of an annual crop, if sowing is done a week too early or too late, harvest potential can be affected. However, within each timeslot (henceforth called work-period), the number of days that are actually suitable for work depends largely on weather conditions. Tilling, for example, should not be done if the soil is too wet as it would result in a top soil layer too compact for the next crop to be sown. Moreover, the weight of the tractor can cause deep soil compaction, which may jeopardize harvest potential for the following years.

In 1955, Kreher formalized this notion under the concept of workable days (Kreher, 1955). A workable day, for a given practice, is a day that provides conditions that are agronomically correct for work. Workability criteria depend on the type of practice considered, since they are not all equally sensitive to weather conditions, and on the type of technique or machinery used (a workhorse does not damage a wet soil as a tractor does).

Because of weather variability, the number of workable days for a given work-period varies from one year to the next. This implies that some years the farmer's workforce and machinery will be oversized and other years they will be undersized. Kreher thought that if a farmer could know the frequency of each type of situation, he would be able to adapt his workforce and machinery according to an objective level of risk. However, Kreher did not provide a detailed method to achieve this.

Workable days were studied extensively during the 1960's - 1980's in France and in North America. Research focused mainly on soil tillage in arable crops. The first method for determining workable days was introduced by Reboul in the early 1960's (Reboul, 1964). It was based on the direct observation of the farmers' practices over long periods of time (10 years). He considered that "good" farmers (i.e., farmers producing high average yields) are well qualified to determine work-periods and to judge if conditions are agronomically correct. His method aroused much interest and became widely used in France, but its length (10 years) and lack of precision were major drawbacks (Reboul, 1985). Besides, each study was specific to a small area and could not be generalized to other areas with different soil types or climates.

Reboul (1985) thought that if a relation could be found between workability and meteorological factors, the constraint of the time necessary to establish workable-day references could be removed. Modelling has two advantages : it requires reduced data collection compared to the direct observation method, and once the relationship has been established, workability can be calculated for any year for which the appropriate weather data is available. Frequency analyses on workable days can therefore be carried out on larger datasets than with the observation method. In 1975, mathematician Maamoun succeeded in modelling workability for soil tillage, with a very simple water budget derived from rainfall in the French Champagne region (Reboul and Maamoun, 1983).

From then on, the improvement of computing and programming capacities allowed researchers to elaborate more complex and precise workability models for soil tilling. The next step was to try and make models that could be generalized to any type of soil. Rounsevell (1993) wrote a review of the models produced during that period. The main advances lay in the prediction of soil moisture through more flexible and precise water budget models. Building a workability model from a soil moisture budget model is quite simple : moisture is calculated and then compared to a threshold value in order to determine whether the soil is suitable for tilling. Generally speaking, the most recent research on soil workability tends towards more sophisticated, deterministic models in which statistical relations are gradually replaced by physicochemical relations.

The difficulty lies in determining the threshold values. Rotz and Harrigan showed that their workability model for field machinery operations was extremely sensitive to small variations in the threshold values (Rotz and Harrigan, 2005 ; Rotz *et al.*, 2012). Yet, most of the models elaborated prior to the 1990's made use of threshold values deduced from observations of the farmers' practices. According to Cerf, although farmers are good at analyzing soil parameters, they are not always objective when assessing workability (Cerf *et al.*, 1998). Their decisions are biased by their personal situation (Cerf and Sébillotte, 1997). Therefore, when farmers' expertise is required, it is necessary to level this bias through the experimental protocol. Researchers like Mueller have tried to bypass the farmers' opinion by determining workability directly from soil parameters (Mueller *et al.*, 2003). This requires that soil optimum

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workability be precisely defined by the resulting soil characteristics.

Workable days were first studied as a tool to help mainstream work on the farm. They are still used as such in modern whole-farm models. However, Rounsevell predicted that modelling would open new perspectives of use : the same way a workable-day model can be used to analyze past weather data, it can also be used to predict future workable days provided that the simulated data is available (Rounsevell, 1993). The concept of workable days can thus provide a new point of view on climate change. It can help to understand how new trends in weather patterns can affect practices in the future (Cooper *et al.*, 1997).

Workable days have been studied extensively for arable crops but never, as yet to our knowledge, for vineyard management, although this activity is particularly prone to peak workloads caused by weather variability. In addition, climate change has become perceptible in many vineyards across the world (Hannah *et al.*, 2013). In the Loire Valley in France (80 000 ha of vineyards from Nantes to Sancerre), average temperature of the growing season (April-September) increased by 1,6 °C between 1960 and 2010, whereas minimum and maximum temperatures increased respectively by 1,3 °C and 2,0 °C (Neethling *et al.*, 2012). A significant break point in maximum temperatures was determined for all stations in the Loire Valley at the end of the 1980's, whereas for minimum temperatures, this statistical break point varied from the beginning of the 1980's in Nantes and Angers to the end of the 1980's for the rest of the area (Bonnefoy *et al.*, 2013). Using data prior to this statistical break point, calculations of Huglin index resulted in cool temperate climate in Nantes, Angers, and Tours, whereas using more recent data, indices for these weather stations shifted into temperate climate. Further inland, the Huglin index for Saumur shifted from temperate to warm temperate climate during the last decade (Mérot *et al.*, 2012 ; Neethling *et al.*, 2012 ; Bonnefoy *et al.*, 2013).

Besides temperature increases, other weather parameters are being affected by climate change in the Loire Valley. In Montreuil-Bellay for instance, according to the INRA weather records the vineyard now gets over 1500 hours of sunlight a year during the growing season, against 1200 hours in the 1970's. Over the same period, global radiation increased from 3000 MJ/m² to 3500 MJ/m². Average rainfall remained stable but interannual variability increased. The combination of these factors causes water loss through evapotranspiration to rise by 1 % every year (Barbeau, 2007).

It is now well known that the complex interaction between weather factors and soil characteristics at vineyard plot scales plays a major role in the quality of the grape and the sensory characteristics of the wine (Dirninger *et al.*, 1998 ; Morlat, 1998 ; Tesic, 2001 ; Van Leeuwen *et al.*, 2004 ; Carey *et al.*, 2008 ; Morlat, 2010 ; Neethling, 2010). These interactions can be synthesized into three variables : earliness of the vine cycle, water supply, and vigour potential (Morlat *et al.*, 2001). For this reason, over the past two decades, a research effort was made to provide winegrowers with methods and levers to steer their vineyards through changing environmental conditions. Many of these levers are actually viticultural practices (Coulon *et al.*, 2010). However, the issue of the practices' own sensitivity to weather factors has so far been left aside. In other words, some techniques or machinery may become unsuited to future climate conditions.

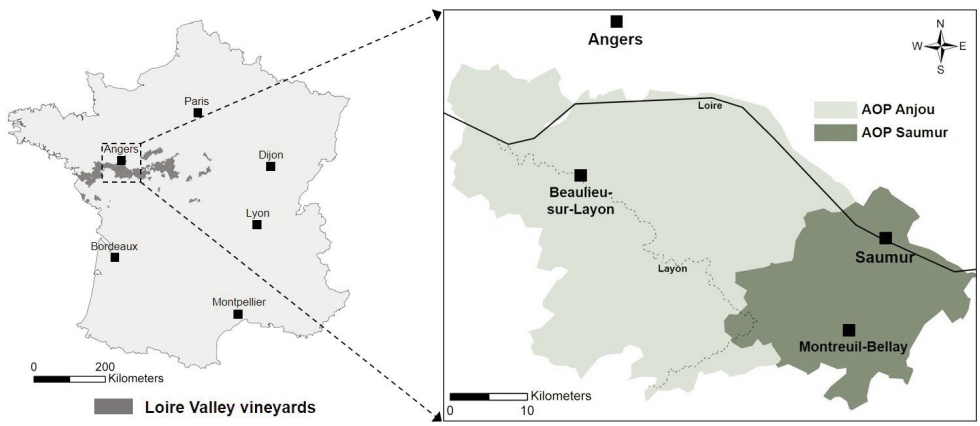


Figure 1. The Anjou-Saumur area in the Loire-Valley, France. AOP, Appellation d'Origine Protégée (Protected Designation of Origin (PDO) in English).

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The purpose of this study is to introduce a method to analyze the sensitivity of viticultural practices to weather variability, based on the modelling of workable days.

MATERIALS AND METHODS

1. Data collection and selection of a case study : pesticide spraying

The study focuses on the Anjou-Saumur area, located in the Loire Valley (figure 1). At the beginning of 2011, a survey was carried out to collect the winegrowers' opinion on practice sensitivity to weather factors. A panel of 12 winegrowers considered as « good farmers » according to Reboul (1964) was chosen to get a significant picture of the Appellation in terms of estate sizes and farming systems. This panel represented different vineyard sizes ranging from 6 ha to 55 ha as well as three farming systems (conventional, integrated, and organic). The survey encompassed 21 viticultural practices commonly used in the Anjou-Saumur Appellation, providing for each one data related to the work-period, techniques and machinery involved, weather constraints that affected practice feasibility, and criteria used by winegrowers to decide whether conditions were suitable or unsuitable for work.

Among the 21 practices considered, most winegrowers pointed out pesticide spraying against powdery and downy mildews as the most sensitive practice regarding weather parameters. These diseases, frequent during the vegetative season, can jeopardize the harvest and winegrowers have to act quickly at the first signs of outbreak. Pesticide spraying against mildews was thus selected for the purpose of modelling workable days.

2. Description of pesticide spraying

All the winegrowers interviewed use a sprayer carried on the tractor. Different technologies have been developed for spraying the product onto the vine, but the technical procedures do not deal with them differently regarding weather conditions. One winegrower only mentioned that the risk of drift depends on the type of spraying technology.

There are two main types of products to spray against mildew. Contact products form a protective coating on the vine until wind or rain weathers them off. Systemic products penetrate into the vine within a few hours and remain efficient for 12 to 14 days. The former can be used in any farming system, whereas the latter are forbidden in organic farming. Because contact products are exposed to weather conditions, a winegrower will need to look at weather forecasts for several days beyond the scheduled application date, in order to know whether it is worth spraying or if it is better to wait, depending on disease pressure. Conversely, when using systemic products, it is sufficient to know the weather conditions on the day and time of application only. Although the winegrowers' strategies differ from one type of product to the next, workability criteria *stricto senso* are the same for both types.

3. Model parametrization

The survey provided most of the data required to build the model, that is : the work-period, the weather parameters involved, the corresponding threshold values, and the period of measure in each day. The information collected was checked and completed by referring to the technical procedures provided by technical institutes and governmental agencies (DRAF/SRPV de Lorraine, 2002 ; Henriot, 2003 ; DGAL/SDQPV, 2005 ; CORPEN, 2006 ; Chambre d'agriculture de Maine et Loire, 2006 ; InterLoire, 2008 ; Chambre d'agriculture des Deux-Sèvres, 2013 ; Chambre d'agriculture des Landes, undated). The information collected among the winegrowers was found to match closely that of the technical literature.

Weather parameters : According to the technical standards, there are six weather parameters that impact the quality and efficiency of spraying : rainfall during the spraying process, rainfall right after the spraying process, leaf wetness duration, temperature, hygrometry, and wind speed. To be more accurate, soil trafficability should also be taken into account ; however, none of the winegrowers mentioned it as a constraint probably because waterlogging is very infrequent during the summer. Given that building a soil moisture budget model did not fit within the scope of this study, this parameter was left aside.

Rainfall (RR, mm). It should not rain at all during spraying to avoid run-off. Furthermore, according to technical literature, it should not rain for at least 2 hours following spraying, in order to allow time for the product to penetrate into the vine (Chambre d'agriculture de Maine et Loire, 2006). Winegrowers usually plan between 2 and 4 hours of dry weather after spraying. In the model, this parameter was set to 3 hours, which is an appropriate delay for most products.

Leaf wetness duration (LW, h). This factor is not consensual. According to some technical literature, moderate leaf wetness is favourable to spraying as it causes stomata to open up, thus making product absorption more efficient. However, other references

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consider that leaf wetness can cause the product to run off, especially if the water droplets are large (Henriot, 2003 ; CORPEN, 2006). The survey revealed the same discrepancies among winegrowers. Given that weather stations provide no information on droplet size, the 'leaf wetness duration' parameter was set to zero in order to avoid any risk of run-off.

Temperature (T, °C). Generally speaking, spraying should be avoided under hot weather conditions to prevent volatilization resulting in product loss. Thermal conditions for spraying should not exceed a maximum temperature which lies between 20 °C and 25 °C depending on products. Based on the technical literature, this parameter was set to 22 °C, ensuring agronomically correct conditions for most products without being over-restrictive. In addition, due to vine physiology, a lower threshold is considered at a temperature of 10 °C (zero-vegetation point for vines) under which products are no longer absorbed by the plant. Spraying below 10 °C is therefore useless.

Hygrometry (U, %). Hygrometry should be high in order to minimize volatilization. Most technical references recommend 60 % as the minimum acceptable hygrometry, although a few of them recommend 80 %. Furthermore, hygrometry should not exceed 95 % so as to avoid the occurrence of fog, rain, or dew. In the framework of this study, the optimum condition for spraying was set between 60 % and 95 % in terms of hygrometry.

Wind speed (WS, km/h). According to French regulation, spraying is not allowed if wind exceeds level 3 on the Beaufort wind force scale, that is wind speed higher than 19 km/h (Ministère de l'agriculture et de la pêche, 2006). However, this equivalence refers to average wind speed measured at a height of 10 m, whereas wind tends to be weaker closer to the ground. Moreover, the Beaufort scale indicates that beyond a 12 km/h wind speed, flags fly and leaves are constantly rustled, which means that product spray is very likely to drift away from the vine. Technicians seem to consider that the regulation is not restrictive enough to prevent drift and many references recommend a 12 km/h (and sometimes even 10 km/h) wind speed limit (DRAF/SRPV de Lorraine, 2002 ; Henriot, 2003). Wind speed limit for this model was therefore set to 12 km/h.

Work-period : In the case of disease-control practices, the work-period does not necessarily match a specific phenological stage of the vine but rather the period during which parasites are potentially pathogenic. Among the winegrowers interviewed, none of them carries out any spraying against either type of mildew earlier than April or later than August. Observed data recorded since 1999 at INRA's experimental station in Montreuil-Bellay indicates that the earliest date for spraying was on a 24th of April and the latest on a 24th of August. The work-period for downy and powdery mildew control practices was therefore set to 1st April - 31st August, i.e. 153 days.

Spraying timeslots : Weather parameters vary during the course of the day and weather conditions can be unsuitable for spraying in the morning but favourable in the afternoon. The survey showed that half a day of suitable weather is enough for winegrowers to consider taking the sprayer out to the vineyard. For

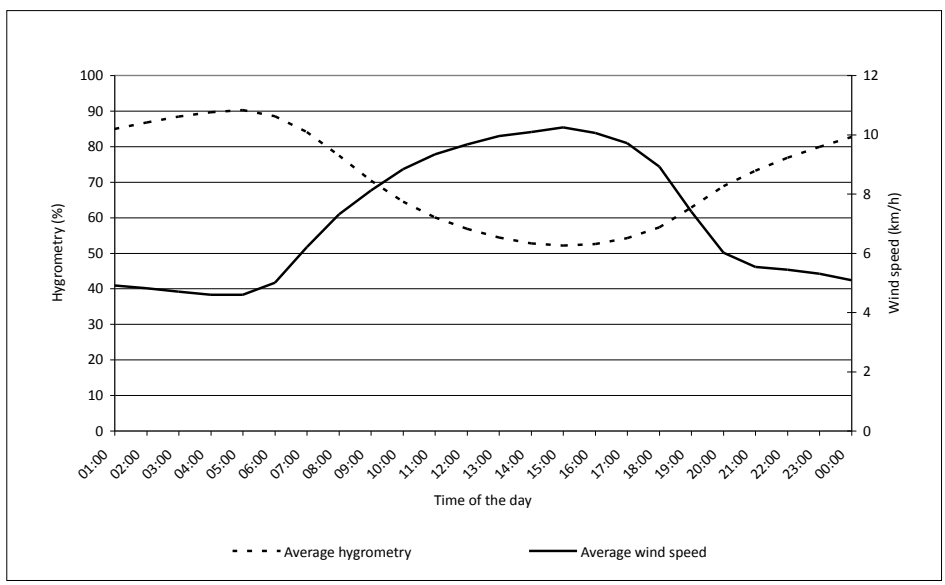


Figure 2. Hourly wind speed (m/s) and hygrometry (%). Average for the 1998-2010 period for the INRA weather station of Montreuil-Bellay.

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instance, a worker can treat up to 7 ha within a five-hour timeslot, depending on the vineyard and the machinery, which is significant given the vineyard sizes in the area. Moreover, half of the winegrowers declared that they would rather spray early in the morning or late in the evening when, on average, hygrometry is higher, temperature is lower, and wind is weaker than in daytime. These climatic trends were confirmed by the analysis of hourly weather data at INRA's experimental station in Montreuil-Bellay (fig. 2). For modelling purposes, days were therefore divided into a morning timeslot (5:00-10:00) and an evening timeslot (19:00-00:00). A day can be considered suitable for spraying when at least one of the two timeslots is suitable for spraying.

4. Model programming

The model was then developed based on the decision rule that determines workability for a given timeslot, which can be expressed as follows : a timeslot is suitable for spraying if during that period all weather parameters are within the acceptable ranges.

The algorithm was programmed using the Visual Basic for Applications language. For each timeslot, the model's algorithm generates six aggregated variables corresponding to each weather parameter, as presented in table 1. The aggregated variables are then compared to a pair of parameters, which represent the minimum and maximum threshold values defined for each weather factor, as presented in table 2.

5. Climatic data

INRA's Agroclim unit in Avignon (south of France) manages the INRA network of weather stations across the French vineyards and provided the necessary hourly data of Montreuil-Bellay available since 1998. The model was therefore tested on the 1998-2010 dataset.

6. Validation data

At INRA's experimental station in Montreuil-Bellay, spraying dates against downy and powdery mildews have been recorded since 1999. Between 1999 and 2010, treatments were applied on average 8 times throughout the season. The actual spraying dates could therefore be compared to the calculated workable days over the 1999-2010 period in order to validate the model.

RESULTS

The variability of the number of workable days was analyzed throughout the 13-year period, as well as the distribution of workable days within the work-period. The impact of each weather factor on workability was

Table 1. Codification of the intermediate variables used by the algorithm for the modelling of workable days.

Raw hourly variables	Aggregation method	Codes for			
		Morning (m) timeslot (5:00-10:00)	Evening (e) timeslot (19:00-00:00)	Lower threshold value	Upper threshold value
Leaf wetness duration	Sum	LWm	LWe	LWmin	LWmax
Rainfall	Sum	RRm	RRe	RRmin	RRmax
Temperature	Mean	Tm	Te	Tmin	Tmax
Hygrometry	Mean	Um	Ue	Umin	Umax
Wind speed	Sum	WSm	WSe	WSmin	WSmax
Rainfall during 3 h following end of timeslots	Sum	RR3m	RR3e	RR3min	RR3max

Table 2. Threshold values used for the modelling of workable days.

Parameters	Lower value	Upper value
Leaf wetness duration	LWmin = 0	LWmax = 0
Rainfall	RRmin = 0	RRmax = 0
Temperature	Tmin = 10	Tmax = 22
Hygrometry	Umin = 60	Umax = 95
Wind speed	WSmin = 0	WSmax = 12
Rainfall during 3h following end of timeslots	RR3min = 0	RR3max = 0

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determined by analyzing the frequency of unfavourable occurrences.

1. Workable-day analysis

The number of workable days varies almost twofold over the 1998-2010 period, 2001 being the worst year with 55 workable days only and 2009 the best year with 104 workable days (table 3). Considering data for 2009, the amount of 104 workable days is the result of 33 days with both timeslots available and 71 days with either one of the two timeslots available, out of a total of 137 timeslots. The proportion of days with both timeslots available is considerably lower for 2001, with 4 days only out of a total of 59 timeslots (figure 3).

A typical analysis that can be carried out using the output data is to observe the distribution of workable days throughout the work-period, as shown in figure 4. Provided the dataset encompasses a sufficiently large number of years, this type of analysis can provide the number of workable days for a given period and a given level of risk. Even though the dataset used for this study consists of 13 years only, a general pattern can be drawn. It is clear that optimum conditions for spraying start as from the second decade of April. By the second decade of May and onwards, winegrowers had 75 % chances of having at least 4 workable days.

2. Analysis of unfavourable factors for spraying

Every time a weather parameter was out of range, thus causing the corresponding timeslot to be unworkable, it was counted as an unfavourable occurrence. Leaf wetness duration is by far the most frequently unfavourable weather factor for spraying, with 46 % of the unfavourable factor occurrences over the 13 years (figure 5). It ranks first each year, though its proportion is noticeably lower for 2005, 2006, and 2010 (figure 6). This can probably be explained by the fact that these three years are the driest years among the 13-year period. Temperature and rainfall contribute to unfavourable occurrences in similar proportions (respectively 19 % and 17 %), followed by hygrometry (13 %). The contribution of wind

Table 3. Output data for the 1998-2010 period

	Years												
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Number of:													
- Workable timeslots	101	74	96	59	76	106	129	124	130	111	125	137	140
- Workable days	79	58	84	55	67	81	93	98	94	85	90	104	99
- Unworkable timeslots	205	232	210	247	230	200	177	182	176	195	181	169	166
- Unworkable days	74	95	69	98	86	72	60	55	59	68	63	49	54
Number of unfavourable occurrences of:													
- Leaf wetness duration	166	203	179	172	175	131	113	100	98	171	143	107	75
- Rainfall	61	53	67	54	66	39	54	37	39	63	67	45	37
- Temperature	54	48	45	75	53	82	65	67	73	15	44	51	69
- Hygrometry	31	27	13	47	41	50	37	59	37	13	48	54	49
- Wind speed	21	12	23	29	21	9	14	5	8	16	8	10	13

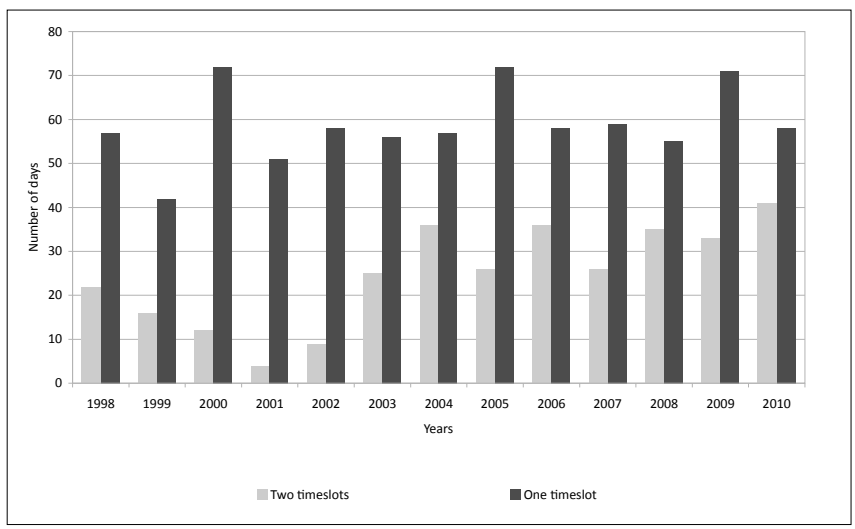


Figure 3. Number of days with both timeslots or one timeslot (either morning or evening) available for spraying.

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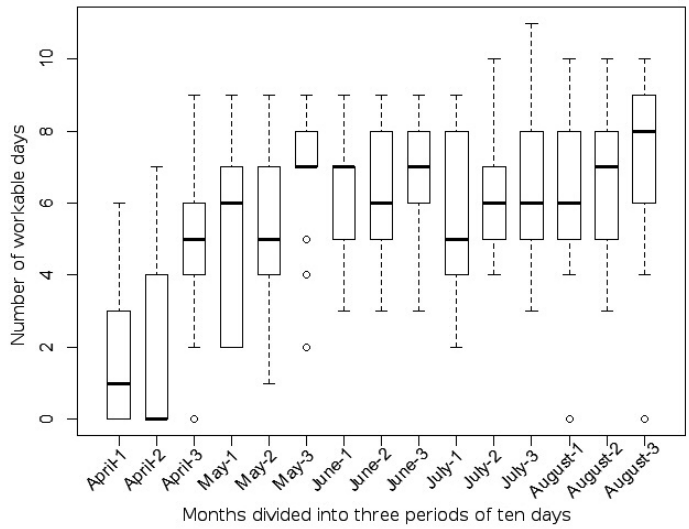


Figure 4. Box-whisker plots. Number of workable days per ten-day period from 1998 to 2010 (whiskers represent the farthest data still within 1.5 interquartile range).

speed to unfavourable occurrences is comparatively low, with only 5 %.

3. Validation

At Montreuil-Bellay, over the 1999-2010 period, a total of 115 treatments were carried out, out of which 32 % were applied on a day which was determined as not workable by the model (table 4).

Analysis showed that leaf wetness duration represents 47 % of all the unfavourable weather factor occurrences involved in these unworkable periods. As it was said before, this factor is not consensual, however the technician in charge of spraying at the station considers that dew is an unfavourable condition. This means that, in some cases, he had to bypass his own recommendations.

In fact, 46 % of the observed treatments applied under unfavourable weather conditions can be explained by a constraint of time: 13.5 % can be due to holidays which keep the workers away from the vineyard and 32.4 % can be attributed to a long series of unworkable days (more than 5), both cases leading to increasing disease pressure and risky sanitary situations for vines and thus forcing the winegrower to relax his workability criteria and spray when possible.

DISCUSSION

This model is based on a strict definition of workable days, it is not meant to represent the decision processes that can sometimes lead a winegrower to lower his workability criteria. Moreover, the 'leaf wetness duration' factor cannot be easily interpreted. In our case, for instance, modelling showed that over the 1998-2010 period, leaf wetness duration was the most problematic factor when spraying against powdery mildew. This result implies the need to clarify the role played by this factor during spraying. Given these two facts, results showed that the model most correctly reproduced decision rules used by winegrowers of the Anjou and Saumur wine regions concerning weather conditions suitability for spraying.

As time constraint explains almost 50 % of the treatments despite unfavourable conditions, it should be possible to significantly reduce this percentage through better weather forecasts as well as better holiday planning.

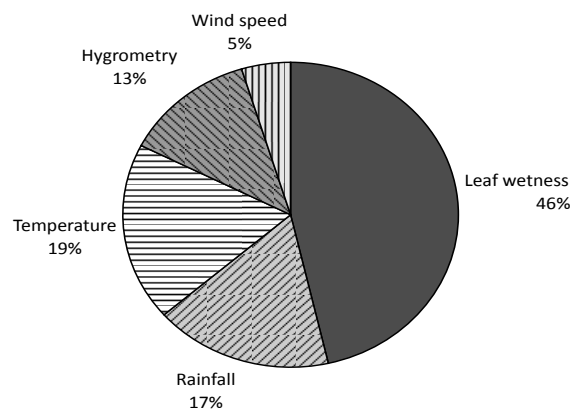


Figure 5. Share of each weather factor in the total number of unfavourable occurrences over the 1998-2010 period.

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The modelling of workable days provides a partial notion only of the stress level winegrowers may experience at a given point in time. For instance, a windy week may be forecast, yet with no disease pressure: in this case, the lack of workable days for spraying is not a constraint. In order to provide a more precise assessment of constraints, such a model should be coupled to a disease propagation model, like the one which is under development at the "Institut Français de la Vigne et du vin" (French Vine and Wine Institute) or the one implemented by Salinari *et al.* (2006). Given that disease cycles are also dependent of weather conditions, the combination of both models could probably help to anticipate critical periods.

In a perspective of climate change, it could be interesting to forecast how workable days may evolve in the future, on the basis of the current techniques and machinery. Since the workable-day model was validated for fungicide spraying, we could try to apply it using simulated meteorological data. For this study, outputs from the Arpege-Climate model of Météo-France were obtained via the INRA Agroclim station in Avignon. The simulated data chosen were those performed with the A1B SRES scenario of IPCC, over de 1960-2100 period. A1B scenario represents a balance across all energy sources (Nakicenovic *et al.*, 2000; IPCC, 2007). However, data are available on a daily basis, not on an hourly basis (Météo France, 2011), therefore it was not possible to calculate workable days as done previously. Another approach was then envisaged, through the characterization of the climatic years using simulated daily data. Workable days have already been calculated for very contrasted climatic years between 1998 and 2010. We formulated the following hypothesis: it is possible to characterize the climatic years between 1998 and 2010 and to assign them a range of workable days; then if we characterize the years between 2011 and 2100 similarly using simulated climatic data, we will be able to classify future years into climatic groups and attribute them a range of workable days.

Only two types of daily variables were common to the 1960-2100 simulated dataset and the observed 1998-2010 dataset: temperature and rainfall. In order to characterize climate during the period of fungicide spraying (April-August), several indices derived from daily maximum and minimum temperature and rainfall were used. For rainfall: total rainfall, number of rainy days, rainfall distribution index, and number of rainy days distribution index; these distribution indexes are derived from the Gini index[1] (Gini, 1921). For temperature: number of days with minimum temperature below 10 °C, number of days with maximum temperature above 27 °C, and cumulated

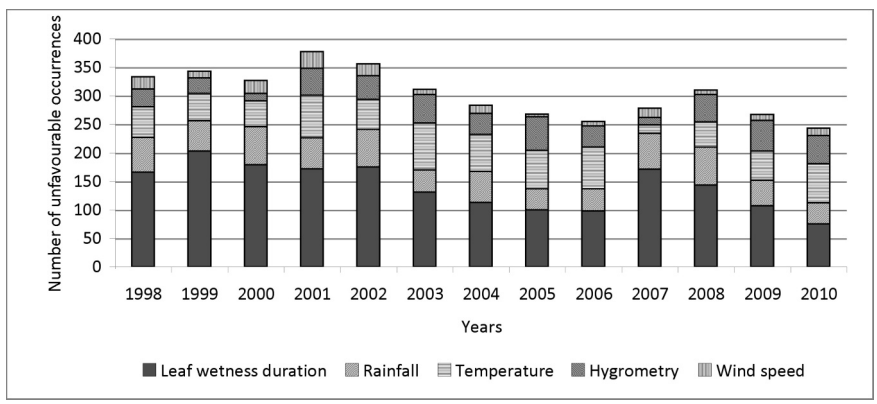


Figure 6. Number of unfavourable occurrences, per weather factor and per year.

Table 4. Number of treatments per year and number of treatments applied on unworkable days over the 1999-2010 period in Montreuil-Bellay.

	Years												
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
Total number of treatments	11	15	10	12	6	7	6	11	11	12	9	5	115
Number of treatments on unworkable days	3	3	5	5	4	1	4	4	3	1	3	1	37
Error rate (%)	27.3	20	50	41.7	66.7	14.3	66.7	36.4	27.3	8.3	33.3	20	32.2

[1]The Gini index measures the statistical dispersion of a distribution in a given population. It is generally used to measure the inequality of income among a country's residents.

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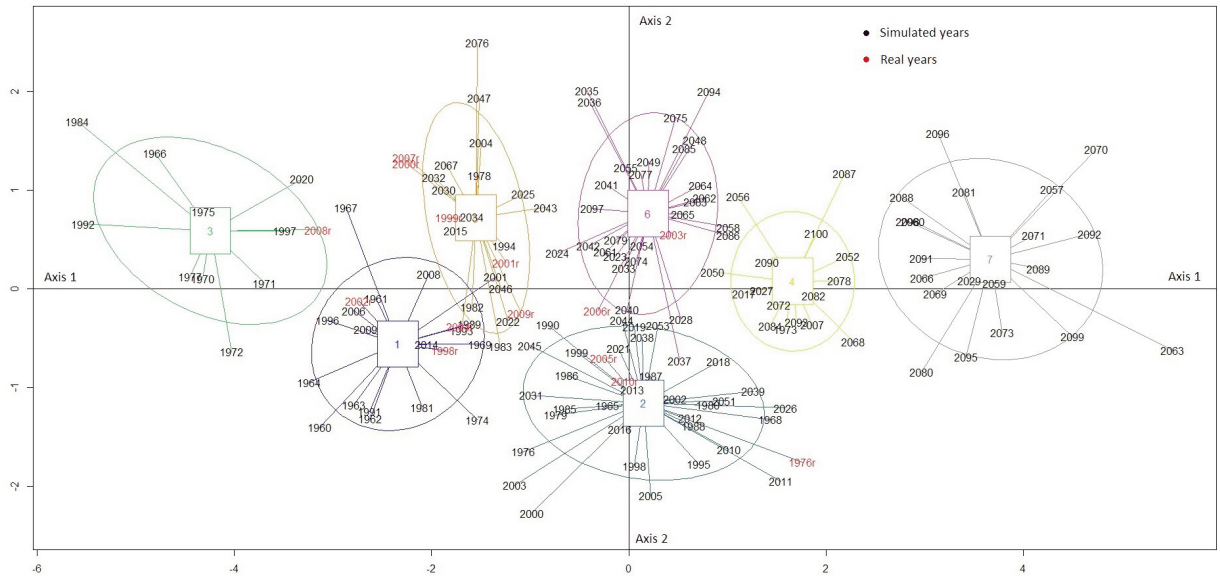


Figure 7. Distribution of simulated years and observed years into climatic groups according to factorial plan 1-2.
Factorial plan 1-2 contributes to 84.5 % of total inertia. Axis 1 (70.3 % of total inertia) represents, from left to right, increasing temperatures and decreasing rainfall; the distribution of rainfall and rainy days also becomes more irregular. The spreading of the years along axis 1 also shows that this axis represents the arrow of time. Axis 2 represents, from top to bottom, a growing number of cool mornings.

growing degree days from 1st of April to 31st of August derived from the Winkler index formula (Winkler *et al.*, 1974). The first two indices were calculated in order to discriminate cool and warm conditions, considering that low temperatures generally occur in the morning and warm temperatures in the afternoon; thresholds were determined by expertise based upon the 1998-2010 series so as to obtain accurate discrimination between years. The seven variables were calculated for two sets of data: observed years (1998-2010) and simulated years (1960-2100).

Appropriate statistical analyses, namely PCA (principal component analysis) and HAC (hierarchical ascendant classification), allowed determining seven climatic groups, from cool and humid to hot and dry (figure 7).

A remarkable fact is that none of the observed past years is situated in groups four and seven. These groups, located on the right side of the graph, are both representative of very warm and dry climates, in which rainfall is highly irregular. Group seven is yet more extreme than group four. Years falling in these groups make up most of the second half of the century. That means that none of the past years between 1998 and 2010 (not even 2003 and its heat waves) can give us an accurate representation of the types of climate that will prevail by the end of the century under conditions of the A1B scenario. The remaining groups contain at least one recent year that is susceptible to give an idea of the number of workable days for spraying. However, a more in-depth analysis shows that the grouping of climatic years does not fit well with ranges of workable days. Group five contains five actual past years with significant differences in terms of workable days (cf. table 3). The lack of reliability between climatic groups and workable days can be explained by the fact that some very important parameters such as wind speed, hygrometry or leaf wetness duration used to calculate workable days are not taken into consideration for the characterization of climatic years. Another factor may be the length of the reference period – only thirteen years of observations – against a sample of one hundred and forty years of simulations. Thus, the lack of simulated climatic variables that could be used directly in the workable-day model cannot be overcome by the type of approach we hypothesised here. However, the exercise proved to be useful since we were able to evidence the complete lack of reference for the second half of the century.

The 1998-2010 period used as a reference for this study was a short sample, yet representative of the present climate variability, from cool and rainy to warm and dry. None of these years was found in the A1B scenario after 2050. Therefore, it is reasonable to estimate that in the next forty years, even if climate becomes warmer and dryer, it will remain within a

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range of variation that has already been experienced. We can assume that the workable days will also remain in the experienced range of variation. In terms of workable days, projections remain sensitive issues beyond 2050.

CONCLUSION

Applied to a perennial crop such as grapevine, the modelling of workable days can be used to identify the major climatic constraints affecting annual cropping practices implemented in a given area. The example of pesticide spraying against powdery and downy mildew, which depends on various weather parameters, showed that the model is able to represent rather well the decision rules used by the growers, even if the practice is complex and some of the parameters not fully understood. Moreover, it is possible to explain the percentage of differences between simulated and observed workable days. Generally speaking, the hierarchy of weather factors will indicate on which levers to focus on in order to improve and adapt vineyard management strategies. The modelling of workable days can be used in a dynamic way by research and development teams to develop innovative techniques, machinery, and inputs adapted to local situations. The method holds even larger potential with the rapid improvement of climatic models, as a workable days model can be used with simulated data as it becomes more complete and precise. The adaptation of vineyard management plans to climate change requires that the issue of workability under future weather conditions be addressed.

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